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Principles for Intelligent Decision Aiding

Susan G. Hutchins

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EXECUTIVE SUMMARY

OBJECTIVE

The Tactical Decision Making Under Stress (TADMUS) program is being conducted to apply recent developments in cognitive theory and human-system interaction technology to the design of a decision support system (DSS) for enhancing tactical decision-making under the highly complex conditions involved in littoral settings or any short-fused, dynamic decision-making situation. Our goal is to present decision support information in a format that (1) minimizes any mismatches between the cognitive characteristics of the human decision maker and the design and response characteristics of the decision support system, (2) mitigates the shortcomings of current tactical displays that impose high information processing demands and exceed the limitations of human memory, and (3) synthesizes numeric data into graphic representations to facilitate the interpretation of spatial data.

RESULTS

The research reported here focuses on developing a DSS that reflects the natural decision-making strategies of humans. Hence, prototype display development was based on decision-making models postulated by naturalistic decision-making theory, such as the recognition-primed decision model and explanation-based reasoning. In addition, human-system interaction design principles have been incorporated which are expected to reduce cognitive-processing demands and thereby mitigate decision errors caused by cognitive overload, which have been documented through research and experimentation. Presenting synthesized information in the form of graphic presentations is expected to reduce the cognitive-processing load for the decision maker when performing situation assessment. The intention is to aid the decision maker by providing information in a way that will minimize the need to maintain information in working memory, reduce information-processing demands, help focus attentional resources on the highest priority contacts, remind the user of actions that must be taken, help make decisions under stress, and support higher levels of situation awareness.

Features offered by the DSS to address errors attributed to limited attentional resources include focusing attention on (1) high priority contacts (i.e., track priority list and alerts), as well as on (2) missing data (e.g., threat assessment), and (3) enabling the decision maker to use more data than are typically used in current systems (such as, track history and comparison to normal values). Current systems require the user to retain previous contact data in memory to compare with the most recent values for critical parameters. Current systems also require the user to rely on recall of vast amounts of information from training and experience. Presenting all known data on a contact in a synthesized way should reduce working-memory requirements and facilitate recognition. Additional potential performance enhancement features, offered by the DSS, include displaying the complete kinematic contact history, presenting graphic displays of location and trends, highlighting missing data, providing alerts, and providing assessments of current contact identity that go beyond what existing systems now present.

RECOMMENDATIONS

Many of the recommendations made by subjects in the initial evaluation of the DSS have been incorporated along with additional features the research team anticipates will further enhance performance. The next phase of the TADMUS program will empirically evaluate the DSS II. Other research issues remain, which include plans for (1) testing the complementary roles of the DSS and

(2) training in critical thinking. Critical thinking is a form of critiquing the currently held threat assessment to ensure one has not succumbed to cognitive biases. An experiment will be conducted to examine whether practice and feedback provided by the DSS (using a modified version of the threat assessment module) enhances training.

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INTRODUCTION

Recent changes in U.S. Naval priorities stress the requirement for Navy ships to operate in the littoral regions of the world, that is, in the coastline regions. Operating in the congested and confined water and airspace close to land presents additional challenges to the tactical decision maker. Littoral operations involve scenarios characterized by rapidly unfolding events that fit multiple possible hypotheses concerning contact identification, intent, available responses, and their consequences. For example, the close proximity of U.S. Navy forces and potential adversary forces greatly complicates interpreting the actions of an inbound aircraft that does not respond to radio warnings. Should the aircraft's behavior be interpreted as an attack profile? Or does the pilot merely intend to harass? Or does the aircraft in question not carry the equipment needed to receive verbal warnings, leaving the pilot unable to receive radio warnings directed toward him and unaware of his precarious position? In extreme cases, there is no clear-cut right or wrong answer about a decision. Rapidly unfolding events result in severe time pressure and severe (often catastrophic) consequences for errors. While current real-time battle-management systems are well-suited to the demands of all-out conflicts, they may not be optimized for littoral situations where human intervention in decision-making is even more important (Office of Naval Technology [ONT], 1992). (Since 70 percent of the world's population lives within 200 miles of the sea, most future contingencies are likely to involve littoral warfare (Mundy, 1994).)

Two unfortunate and highly publicized events focused attention on the difficult types of decisions confronting naval commanders and provided the impetus for this research. In the case of the USS *Stark*, the commander made the decision not to engage an inbound aircraft that was not believed to be a threat to his ship, resulting in 27 U.S. Naval personnel losing their lives. In the case of the USS *Vincennes*, the commander made the decision to engage the inbound aircraft, believing it was a threat to his ship—which turned out not to be a threat, but a commercial airliner—resulting in all personnel aboard the airliner being killed. In recognition of the complex and difficult decisions required in these types of situations, the Tactical Decision Making Under Stress (TADMUS) program was initiated to conduct research in human factors and training technology. The objective is to develop and apply principles that can help avoid these types of situations in the future. This document reports on research conducted under the TADMUS program to apply recent developments in decision theory and human-system interaction technology to the design of a decision support system (DSS) for enhancing tactical decision-making under highly complex conditions.

“NATURALISTIC” AND CLASSICAL DECISION-MAKING PARADIGMS

In the same time frame that these tragic accidents occurred, a radical shift was occurring in the way psychologists viewed human decision-making. Research was now focused on experienced decision makers performing their normal tasks in natural settings. “Naturalistic” decision-making research studies the decision strategies people actually use in bringing their expertise to bear under challenging real-world conditions. These conditions include dynamic, fluid situations; time pressure; high-risk, multiple decision makers; shifting and competing goals; action-feedback loops; and situations with uncertain and incomplete data (Orasanu & Connolly, 1993). Decision-making milieus encompassed under the naturalistic paradigm include hospital emergency rooms, aircrew flight coordination, military command and control settings, process control systems, and police and fire units.

The naturalistic perspective, also known as “everyday cognition,” is based on a belief that cognitive functions “elicited in natural settings (are) likely to differ, either quantitatively or qualitatively from those that occur in artificial or contrived situations; and results from sterile and contrived situations

may not generalize to less constrained and more natural environments” (Salthouse, 1992, p. 982). There is a growing body of work that demonstrates that experienced, real-world decision makers rarely use traditional resource-intensive strategies to make decisions in the face of dynamic, adverse conditions and time-pressure (Kaempf & Militelo, 1992; Klein, 1993). Instead, experts rely on their abilities to recognize and appropriately classify situations—these abilities are based on having much experience in the task domain. Once these experts know what they are facing, they also tend to know what response option to apply, based on retrieving from memory typical responses and outcomes that worked well in past similar situations. They use the limited time available to evaluate the feasibility of that option before implementing it. Experienced decision makers recognize the situation or scenario based on comparing the features of the current situation with stored memory representations, or schemata. Schemata are highly interconnected clusters of knowledge concerning certain situations, or particular problem types, and associated actions or solution procedures (Federico, 1995). Once the situation is recognized, solutions are stimulated by activating these memory representations.

In contrast to the naturalistic perspective, earlier analytical methods applied in decision support systems were primarily used for option generation and evaluation, rather than for situation assessment. Traditional decision theorists argue that optimum decision-making involves thorough analysis of all the available data and evaluation of all possible hypotheses; these approaches tend to rely on extensive calculations designed to arrive at optimal solutions. Processes for making decisions where the person weighs the pros and cons of various options and selects the option that provides the most benefit are described in the decision-making literature. The extensive time requirements and complicated mathematical calculations involved (e.g., Multiattribute Utility Analysis), however, are unrealistic for situations requiring rapid decision-making. Generally, these analytical strategies involve the following steps (Kaempf & Militelo, 1992):

- Specify all relevant features of the task,
- Identify the full range of options,
- Identify the key evaluation dimensions,
- Identify weights for each dimension,
- Rate each option on each dimension,
- Tabulate the results, and
- Select the best option.

These analytical strategies may be appropriate for inexperienced subjects making decisions about novel tasks, but not for experienced personnel making real-time decisions. In natural settings, time constraints and the difficulty in assigning weights and rating the dimensions involved render classical analysis techniques untenable. Typically, in realistic settings, experts employ recognition-based reasoning, not classical analytical approaches. Experienced decision makers use their extensive knowledge to seek information, identify and interpret the problem, understand the significance, derive the intention (where possible), model the situation (as time allows), select the action, evaluate the choice, and anticipate the consequence. “This decision cycle is distinctly different from classical models, which are based on the assumption that all options, outcomes, and preferences are known and calculated in advance” (Federico, 1995, p. 106).

Traditionally, research in decision-making has been directed largely toward situations in which (1) decision-makers have sufficient time to generate options, conduct option assessment, and select a

course of action; (2) the consequences of an incorrect response are not immediately severe; (3) decisions are reached via consensus of a group; and (4) workload is manageable. Little research has been conducted into development of tactical decision support systems for use in naturalistic situations characterized by time pressure, high risk, uncertainty and information ambiguity, high workload, team coordination demands, and task complexity (ONT, 1992).

The central hypothesis for the research reported here is that presenting decision makers with decision support tools designed to parallel the cognitive strategies employed by experts, as observed in naturalistic settings, will reduce the number of decision-making errors. This is accomplished by developing the architecture and algorithms to process information the same way research indicates humans do under similar circumstances.

DECISION SUPPORT PRINCIPLES

A case has been made that previous generations of decision support systems are less applicable than a decision support system (DSS) that parallels the cognitive strategies used by domain experts in situations characterized by time-constrained circumstances with uncertain and ambiguous data (Smith & Grossman, 1993). Such systems focus primarily on solution optimization and base decision support on normative models of human decision-making. These authors point out that rarely, if ever, were earlier tactical decision aids intended as psychological models of human cognitive behavior. Instead, these aids performed “complex and burdensome calculations, reducing the workload on personnel, speeding up the dissemination of information, and providing more time for command decision-making” (Tolcott, 1991, p. 44).

FEATURE MATCHING AND STORY GENERATION

We have applied two of these new models of human decision-making—which parallel the cognitive strategies used by domain experts—to the design of a DSS for enhancing anti-air warfare tactical decision-making. These two models that people use in assessing a situation are feature-matching and story generation. The feature-matching model, described by Noble (1989), involves an organization of memory, or “schemas,” and information processing where decision makers use their previous experiences to assess a situation and identify promising actions. Incoming information is categorized, selected, edited, and organized on the basis of a person’s general knowledge about a domain. Both story generation and feature-matching occur under conditions where a large base of implication-rich, conditionally dependent pieces of evidence must be evaluated before choosing an alternative from a set of prospective courses of action. The feature-matching model applies a spatio-temporal dependence, whereas story generation is an example of causal dependence. According to the explanation-based model, decision makers construct a causal model to explain the available evidence (Pennington & Hastie, 1993). At the same time, the decision maker creates a set of alternatives from which an action will be chosen. A decision is made when a story is successfully matched to an alternative in the choice set. Story generation occurs in complex situations where the decision maker may not have all the necessary information or when a series of facts may appear to contradict each other. The decision maker must then develop causal links between these facts to produce a coherent picture of the situation (Klein, 1989; 1993).

The story generation model is based on research which found that jurors develop a narrative story to organize trial information where causal and intentional relations between events are central (Pennington & Hastie, 1992). Pennington & Hastie propose four certainty principles—coverage, coherence, uniqueness, and goodness-of-fit—that govern which story will be accepted, which decision will be selected, and the confidence or degree of certainty with which a particular decision will be made. This organization of the evidence by the decision maker is believed to facilitate evidence comprehension. A central component of this model is that the story the juror constructs determines the juror’s decision. This explanation-based decision process is employed when the body of evidence relevant to a decision is large, complex, and the implications of its components are interdependent.

Feature matching, also referred to as the recognition-primed decision (RPD) model, “occurs when the decision maker recognizes the features of the present situation as similar or identical to those of a previous situation” (Kaempf & Militello, 1992, p. 6). An adequate match triggers recall of information learned about this type of situation; that is, plausible goals, critical cues to be monitored, expectations of what should happen, and a course of action that worked in similar situations. According to this recent approach, expert decision makers may rely on well-developed memory representations to

guide decision-making in new (but similar) situations. The RPD model of decision-making fuses two processes—situation assessment and mental simulation (Klein, 1993). In the simplest case, the situation is recognized as familiar or prototypical, using feature matching, and the obvious response is implemented. In a more complex case, the decision maker consciously evaluates the response, using mental simulation to uncover problems prior to implementing the response. In the most complex case, the evaluation reveals flaws requiring modification, or the option is judged inadequate and rejected in favor of the next most typical reaction.

Situation Assessment

In general, the overall task of responding to anti-air-warfare (AAW) scenarios consists of situation assessment (“what’s going on”) and course-of-action selection (“what to do about it”). Recent theories of decision-making emphasize the importance of situation assessment for good decision-making in naturalistic, event-driven situations. Moreover, they stress that decisions regarding actions to be taken are a by-product of developing the situation awareness that precedes action selection. Klein (1989) has found that usually the situation itself either determines or constrains the response options and that experienced decision makers make up to 90 percent of all decisions without considering alternatives. If the situation appears similar to one the decision maker has previously experienced, the pattern will be recognized, and the course of action is usually immediately obvious. On the other hand, if the situation does not seem familiar, complex RPD will be involved, where the decision maker adjusts the option after evaluating it.

Additional evidence was found in the specific task domain of interest to the TADMUS program, which added support to these findings on the way real-world decision makers make decisions in the context of their normal jobs. Research was conducted to determine decision requirements for command-level decision makers in the combat information center (CIC) of an Aegis cruiser. Analysis of 14 incidents from actual problems revealed 183 decisions. Of these, 103 concerned situation assessments. Results obtained after analysts coded these situation assessments indicated that decision makers arrived at 87 percent of their situation assessments through feature-matching and the remaining 13 percent through story generation (Kaempf, Wolf, & Miller, 1993). The other 80 decisions that were identified from analysis of the real-world incidents mentioned above involved course-of-action selection. These course-of-action decisions served a variety of functions, although relatively few were intended to end the incident. Of these, 20 were intended as a final course-of-action decision, 14 were implemented to obtain more information, 22 to manage resources, and 24 to put themselves in a more favorable tactical position. A recognition-based strategy was also used by decision makers to develop a course of action, accounting for 95 percent of the actions taken in the 14 incidents. The decision makers generated and compared multiple options in only 5 percent of the cases. In line with these findings, the TADMUS program has adopted the position that decision-aiding systems should assist in the decision-making *process* and focus on aiding the situation-assessment portion of the decision-making task.

A DSS was developed to support decision-making processes that research has shown are used by decision makers in real-world settings. Specifically, the DSS parallels the strategies used by experienced decision makers to perform situation assessment (Nobel, 1989; 1993). This approach to supporting the user’s intuitive approach to dealing with dynamic decision-making situations should produce tools that are both more easily understood and used, and that more effectively “exploit the decision maker’s knowledge and expertise which might facilitate adaptation to complex, novel situations” (Cohen, 1993, p. 265).

HUMAN-SYSTEM INTERACTION DESIGN PRINCIPLES

The vast majority of research on human-computer interaction has been devoted to characteristics of displays that impact human perception, such as symbol legibility or detectability, and on relatively simple cognitive functions, such as memory tasks. Fewer efforts have been devoted to understanding the effects of the format and manner in which information is presented on more complex levels of human cognition, for example, decision-making. Consequently, principles that can be applied to the design of the interface between the user and a decision support system for enhancing cognitive processes, particularly in stressful, dynamically changing situations, are not available to any significant degree (ONT, 1992).

GRAPHIC PRESENTATIONS

Several advantages are offered by graphic presentations over a text-based presentation format (Larkin & Simon, 1987). Graphic presentations should (1) reduce the amount of mental computation required to perform tasks and (2) allow users to spend less time searching for needed information. Casner (1991) elaborated on these ideas and found that graphics allow users to substitute less demanding perceptual operations for more complex logical operations. For example, determining a change in altitude (and the degree of change) is immediately apparent when the user glances at the track history module. (Note that the words contact and track can be used interchangeably. Refer to figure 1 in the section that describes the decision support system.) The track history module is located in the upper right-hand corner of the display. The objective for this module is to facilitate the contact identification process by providing information that is integrated to support a recognitional decision strategy. The track history module depicts a contact's speed, altitude, course, and range on a two-dimensional graphical display along with a geometric representation of both the contact's worst-case weapon-release envelope and own-ship's weapons coverage. A large amount of parametric data is portrayed graphically for rapid assimilation by the user. The user can see, at a glance, a synthesized picture of the contact's behavior. Compare this rather simple perceptual operation to the more complex logical operation involved in current operational systems that require the user to recall and subtract numerical values for past and current altitudes.

Graphics also allow users to omit steps that are otherwise necessary when performing a task without a graphic. An example of this advantage is also illustrated in the track history module, which includes templates indicating weapon's coverage for both the inbound contact and "own-ship." To determine whether the aircraft is within its weapon's launch range, there is no need to recall the specific launch-range values and then compare them with the aircraft's current range. Instead, the user can determine if the aircraft is within its launch range by a quick glance at the display.

Graphics help users save time when searching for needed information when several related dimensions of information are encoded in a single graphical object. This is accomplished by integrating the kinematic parameters of speed, course, altitude, bearing, and range for a contact. The user can see, at a glance, a synthesized picture of the contact's behavior. Compare this process to reading, in a text-based format, the individual parameters that must be integrated by the user into a coherent picture of the contact's behavior.

TACTICAL DECISION-MAKING TASKS

The global tactical decision-making task involves identifying and responding to numerous contacts. When an aircraft (or a surface contact) is detected, the CIC personnel work as a team to determine its identity and to try to determine whether or not the aircraft poses a threat. The high degree of inherent ambiguity associated with contact information can often make threat assessment a very difficult task. This is because many pieces of data fit multiple hypotheses concerning threat assessment. The global response choices (that is, engage, monitor, do nothing) are largely determined by the ship's orders and the current geopolitical situation. Specific actions (such as, change course, issue verbal warnings, illuminate with radar, challenge with other sensors, etc.) depend on the local conditions and the relative positions of the inbound contact of interest and own-ship. Determining which of these actions is likely to be effective depends on maintaining an accurate threat assessment which requires "continual updating according to recurrent situation assessments" (Sarter & Woods, 1991, p. 52).

This decision problem presents a highly challenging cognitive task, that is, making inferences and deductions from incomplete and uncertain information derived from multiple sources and relating to several concurrent threats (or potential threats) under time-compressed conditions. The cognitive functions performed by the tactical decision maker are both data and resource limited (Norman & Bobrow, 1975). Decisions are resource limited by the mental resources of the decision makers, who must maintain large amounts of information in memory under conditions of high workload and stress. The decisions are data limited by the inability of the sensors to provide complete, error-free, unambiguous data to support the identification process. In particular, the experimental scenarios were designed to follow the pattern of being set in an ambiguous situation, where one or more threats of uncertain origin and uncertain intent approach either own-ship or the ship being protected and may not respond to warnings. Scenarios were designed to be highly ambiguous, as this quality of uncertainty is indicative of the types of decisions to be made in current and future scenarios.

THREAT ASSESSMENT

In the AAW problem, threat assessment is particularly difficult because the available information is often incomplete or ambiguous. The ambiguity could be due to (a) the information transmission characteristics of the transmission medium, such as a radar transmission or a radio report that is only intercepted on an intermittent basis; (b) deliberate deceptive actions (such as radar jamming) by the pilot flying the aircraft; or (c) the overlapping classification categories typical of many parameter measurements. For example, aircraft can typically fly at altitudes ranging between 2,000 and 40,000 feet. Generally, an aircraft that is flying above 20,000 feet is not considered to be a threat. Conversely, an aircraft below 10,000 feet is considered to be more of a potential threat. However, aircraft flying in the middle range, (that is, below 20,000 feet and above 10,000 feet) can be much more difficult to categorize. Because many aircraft do fly in this middle range, other variables need to be considered in conjunction with altitude. This same situation of overlapping categorization categories exists for several other variables. These variables include radars found on both threat and non-threat platforms, country of origin, and measures of course and speed. In the case of speed, for example, when an aircraft flying at a low altitude decreases speed, this could be viewed as indicative of a threat action (that is, slowing down in order to obtain better targeting information). However, at the same time, there could be other viable explanations for an aircraft's decreasing speed.

If the decision maker had access to all data about a contact, approximately 12 variables would be used to determine identity and to infer intent. Two or three of these items, alone, do not provide definitive answers because, in many cases, these parameter values do not fall within clear-cut ranges for a

particular assessment category (i.e., threat, nonthreat). Thus, a single time slice of information provides an incomplete picture of the situation. In the dynamic, ambiguous conditions characteristic of littoral operations, the rate and direction of change (data history) can help one better assess the threat and predict the future state of the situation. When the incoming information changes over time, the integration of information as it changes can help the user extract the message (Kirshenbaum, 1992). The DSS was designed to do precisely this: to facilitate the integration process and present a synthesized picture of the situation to the user in a format that can be quickly assimilated. The variables used to develop a threat assessment can be divided into two classes: sensor information (raw or computer-processed information) and the contact's response, or lack of response, to actions taken by the team. These other actions, and the integration of the information received via the contact's response or lack of response to them, are needed to clarify the tactical picture.

SITUATION AWARENESS

While recent increasing interest among researchers about the concept of situation awareness (SA) has generated a debate on the precise definition of this term, most researchers acknowledge the importance of the concept. In general, SA refers to the decision maker's moment-by-moment ability to monitor and understand the state of the complex system and its environment (Adams, Tenney, & Pew, 1995). These authors state the essential idea, which is that, when emergencies arise, the completeness and accuracy of the decision maker's SA are critical to the ability to make decisions, revise plans, and manage the system. Specific decision-making tasks included under SA include the ability to (1) maintain an accurate perception of the surrounding environment (both internal and external to the ship), (2) identify problems and/or potential problems, (3) recognize a need for action, (4) note deviations in the mission, and (5) maintain awareness of tasks performed (Shrestha, Prince, Baker, & Salas, 1995). To maintain an accurate SA, the decision maker should take into account both information that is available and that which can be activated from memory (Sarter & Woods, 1991).

However, a difficulty arises as a result of the heavy workload imposed by this process. Memory load easily exceeds human capacity when the decision maker is faced with several concurrent contacts of interest, all of which have numerous associated data items (i.e., as many as a dozen), some or all of which may change over the course of the scenario (e.g., intelligence, active radar emitters, various kinematic parameters, etc.). Moreover, changing parameters may impart different interpretations to what is occurring. In some cases, the moment-to-moment attentional demands of a tactical situation are relentless and unforgiving (such as a terrorist aircraft directly inbound toward "own-ship" that can result in "task fixation"). Sometimes relevant background knowledge is unavoidably incomplete (such as an unfamiliar aircraft); and sometimes the decision maker is already thinking and working as hard as possible, even when there are no unanticipated events during a high-contact density (Adams et al., 1995). These instances provide a few illustrations of situations that can challenge situation awareness.

Complex information-gathering and processing systems have been designed to aid the decision maker in the past. However, these systems often increase the decision maker's burden due to the inherent system complexity and the failure to design them so they will fit the user's cognitive-processing limitations. Often, these systems require operators to perform difficult cognitive tasks under heavy workloads. They must perceive, synthesize, and determine the relevance of a continual stream of incoming information, often pertaining to several concurrent contacts, while projecting future anticipated events and making decisions about actions to be taken. Decision makers must assess, compare, and resolve conflicting information, while making difficult judgments and remembering the status of critical contacts along with the contact's response to actions taken by the CIC

team. These decision-making tasks are interleaved with other required tasks, such as keeping other team members informed (both on and off the ship). Furthermore, these complex tasks are performed under conditions where adverse environmental (noise, vibration, temperature extremes, etc.) and internal stressors (boredom, fatigue, anxiety, and fear) are part of the environment.

LIMITED HUMAN COGNITIVE-PROCESSING CAPABILITIES

Since there are limits to the cognitive-processing capability of humans, the system must provide the needed information in a format that best supports the user operating under dynamic decision-making conditions. It may be the case that current systems are inadequate to support the cognitive-processing demands required by certain littoral scenarios or in any short-fused, ambiguous decision-making situation. For example, according to Gruner (1990, p. 41), the USS *Vincennes*' officers and system operators "could not make better decisions because they did not have time to confirm or deny the information uncertainties presented them." Gruner maintains that the rapid pace involved in these types of situations can exceed the capacity of the human to comprehend the rapid flow of information presented by complex systems. In the case of the *Vincennes*, the CIC team had 3 minutes and 40 seconds to make their decision. This includes the time required for the operators to perceive and interpret sensor data and for the commanding officer to make informed judgments from these data (Roberts & Dotterway, 1995). The result of the human's limited cognitive-processing capabilities is that the decision makers may fail to remember critical pieces of data, overlook stored information, draw hasty conclusions, and produce flawed answers.

Simon (1978, p. 273) states, "...the human information processing system...operates almost entirely serially, one process at a time, rather than in parallel fashion. This seriality is reflected in the narrowness of its momentary focus of attention." However, the AAW problem forces the decision maker to operate in a parallel-processing mode when several contacts demand attention at the same time. The requirement to monitor and maintain an accurate situation awareness for these concurrent contacts, over the course of the evolving situation, imposes an additional load of strategically managing the overall situation. Several researchers have argued that "managing the attentional and conceptual processes that permit cogent SA involves significant cognitive resources" (Adams et al., 1995, p. 91; Endsley, 1988). Having to handle several concurrent tasks can place an unrealistic cognitive load on the decision maker. Typical examples of such tasks are prioritizing contacts and the associated actions to be taken by the team, updating the status of critical contacts, responding to the other requisite tasks in the queue, and, more generally, of strategically managing the workload of current multitask systems under dynamically changing scenarios.

A major advantage offered by the experimental DSS is that it should "buy time" for the user by (1) performing many of the cognitive-processing tasks for the user and (2) by presenting information in graphic format. The DSS will synthesize much of the information used to develop situation awareness and present a coherent picture of the situation to the user. This integrated picture will be portrayed graphically—rather than in the current text-based format—which should further reduce the amount of time required to assimilate this information. By performing several information-processing steps for the decision maker, the decision maker's limited cognitive resources can be used for the types of decisions requiring human abilities (e.g., the decision on whether to engage).

WORKING-MEMORY REQUIREMENTS

An essential information-processing step required by this task—and one that levies a heavy load on working memory—involves integrating kinematic and sensor variables and maintaining an awareness of changes in these variables over time. Changes in a contact's behavior, such as decreasing altitude, increasing speed, changes in electronic emissions, etc., can provide key indicators of possible hostile intent. With current systems, concerning a particular contact, the decision maker receives numerous reports from CIC team members who provide various pieces of the overall tactical picture (such as kinematic parameter values, active electronic-emitter identifications, and behavioral responses of the

contact in response to queries by the team). Some of this information is also displayed in a text-based format for the user when a contact is “hooked” (that is, selected for display) by the decision maker. However, to recognize a change in certain variables, current systems require the user to retain parameter values in short-term memory in order to recognize a change in the parameter, such as altitude.

When the decision maker is monitoring several concurrent contacts (such as cycling through three or four contacts in a 1-minute period), human working-memory capabilities may quickly be surpassed. To detect a change in a critical parameter value, the decision maker must maintain the parameter values for the contacts of interest in working memory as he or she cycles between several contacts. For example, the decision maker must be able to recall that contact 7022 was at a 14,000-foot altitude 1-minute ago, and then subtract the current altitude value of 10,000 feet, which will then indicate the aircraft is in a rapid descent. The DSS was developed to aid the decision maker by performing several of these cognitive-processing tasks, thus, reducing the cognitive load for the user. By presenting the synthesized picture of the contact’s behavior over time, through the use of graphical displays, critical changes should be immediately apparent to the user.

A second memory-intensive task involves maintaining (in working memory) a current list of actions taken by team members, the contact’s response to these actions taken by the CIC team, and pending actions. Research has established that “memory is limited and that list maintenance is effortful and fallible—more so if the list must be ordered, and still more if the membership of the list must be dynamically reordered and modified during retention” (Bower, 1970, as cited in Adams et al., 1995, p. 91). The DSS should reduce the cognitive effort required for distributing attention among the many contacts to be resolved and their attendant required actions. Working-memory requirements should be reduced by having the DSS act as an intelligent “assistant,” reminding the user what actions are to be taken and when.

A third way the DSS will reduce memory and information-processing requirements is by displaying templates depicting weapons’ envelopes for both the inbound contact and “own-ship.” This should facilitate critical comparisons and judgments concerning timing of actions. During a scenario, decision makers have to either rely on memory to recall the launch range for various weapons or query a team member for this information—with both of these methods wasting limited resources. The high-workload and high-tempo characteristic of littoral scenarios produce a stressful decision-making environment. The phenomenon that increasing stress leads to decreasing working memory is well documented (e.g., Hockey, 1986). Moreover, the latter method for obtaining the desired information wastes limited resources by increasing the communications load and requiring more time to wait for a team member’s response to the query.

Under these high-tempo and high-workload conditions, human memory and attentional resources can easily be surpassed. Several cognitively resource-intensive information-processing steps are eliminated for the human decision maker by having them performed by the DSS. We predict that the decision support tools will reduce the cognitive workload imposed on the decision maker in the following three ways: (1) by reducing the amount of information processing to be performed, (2) reducing working-memory requirements, and (3) assisting the user in allocating limited attentional resources.

REDUCING HUMAN ERROR

The study of human cognitive processes and related error mechanisms has gained rapidly increasing interest in the past decade. Rasmussen (1987) argues that the emphasis in attempting to understand human errors must shift from tasks to the human-task mismatch. For example, Gruner

(1990, p. 39), in discussing the *Vincennes* incident, maintains that “the system was poorly suited for use by human beings during rapid military action.” He ascribes this lack of suitability to a human-machine mismatch between the rate of data flow possible with modern computer systems that can process and display information at phenomenal data rates and the “comprehension capability of users which has remained almost static for thousands of years.” This causal approach to understanding human error is based on the premise that errors are rarely random and can be traced to causes and contributing factors. Once these contributing factors are identified, they can be mitigated.

The impact and vulnerability of systems and human interfaces, because of incompatibilities between the way people perceive, think, and act, are documented in popular and technical literature (Buck, 1989; Casey, 1993; Norman, 1988; Perrow, 1984; Wilson & Zarakas, 1978). Newly developed systems will succeed or fail based on our ability to minimize these incompatibilities between the characteristics of the things we create and the way we use them. There are many well-documented instances of critical systems or parameter changes going unnoticed or unheeded because the operating procedures, or the human machine interface, provided no historical trace. For example, an unnoticed increase in altitude contributed to the shoot down of the Iranian airbus by a U.S. Navy ship—when the team mistakenly believed the aircraft to be descending—because there was no historical trace to make the aircraft’s actual *increasing* altitude apparent (Dotterway, 1992). Five personnel in the USS *Vincennes*’ combat information center, all viewing separate displays, reported the aircraft as descending, while the Aegis data tapes later revealed a flight pattern of ascent (Roberts & Dotterway, 1995). One of the official investigations of this incident, the Fogarty Report (1988, p. 45), states that “stress, task fixation, and an unconscious distortion of data may have played a major role in this incident.” A panel of five psychologists from the American Psychological Association (APA) who testified before Congress concluded that there were “predictable failings of human judgment under intense stress compounded by complex technology [which] clearly contributed to the accidental shooting of Iranian airliner Flight 655” (APA, 1988, p. 4).

It is generally accepted that between 60-80 percent of the accidents and malfunctions in transportation, manufacturing, process control, weapon, and other systems are attributable to human error (Senders & Moray, 1991; Van Cott, 1993; Weiner, 1994). Reducing tactical decision-making errors is one goal of the TADMUS program. The following section presents a brief review of an experiment conducted to develop a baseline on tactical decision-making performance in response to fairly stressful scenarios. The last section of this chapter describes the experimental DSS modules and the way they are hypothesized to enhance tactical decision-making performance.

TADMUS BASELINE EXPERIMENT

Early research involved data collection in the Decision-Making Evaluation Facility for Tactical Teams (DEFTT) Laboratory using simulated existing shipboard displays to establish a baseline on decision-making performance. The purpose of this effort was to document baseline decision-making performance for experienced naval officers. During the baseline phase of testing, a detailed understanding was developed of the cognitive processes underlying the various tasks involved in situation assessment—and where the bottlenecks occur. This understanding was then used to design the way the information is presented to the user to facilitate performance of the required tasks.

SUBJECTS

This study focused on the command-level decision makers of an anti-air-warfare team on an Aegis cruiser—the commanding officer and the tactical action officer. Subjects in the study consisted of 6 commanding officer/tactical action officer teams drawn from 12 active-duty Naval personnel; some were from training commands, while others were from operational commands aboard ship or assigned to group staffs.

PROCEDURE

Data were collected in the DEFTT Laboratory, a six-station test-bed environment that simulates console positions in a Navy Aegis cruiser combat information center. (For a detailed description of the DEFTT Laboratory, see Hutchins, 1996.) Four stations were filled by confederates (active-duty Navy personnel) who play anti-air-warfare support-team member roles. These roles included the anti-air-warfare coordinator, identification supervisor, tactical information coordinator, and electronic warfare supervisor. After approximately 1½ hours of orientation concerning the laboratory and training using the computer consoles, the subjects engaged in four scenarios. Each scenario was about 25 minutes long and contained between 11 and 14 contacts of interest per scenario, in addition to numerous background contacts.

TREATMENT OF DATA

Team communications were recorded on a multichannel audio recorder; these communications included all intrateam exchanges, as well as all communications with simulated off-ship personnel. Audio tapes were used to produce verbatim, time-stamped transcripts of all team communications. A modified version of the TapRoot® Incident Investigation System (Paradies, 1991; Paradies & Unger, 1991) was then applied to identify errors. The objective was to identify tactically significant errors committed during the scenario. Tactically significant errors were defined as those errors that may lead to loss of life or significant political embarrassment. The following criteria were used for counting an error as tactically significant: (1) loss of situation awareness, (2) failure to take defensive action when within the weapon's range of an approaching contact, or (3) a violation of rules of engagement (ROE). Video recordings were made of the commanding officer and tactical action officer computer screens. All audio and video recordings were then analyzed in detail. (For a more detailed coverage of the methodology and results, see Hutchins and Westra, in preparation.)

RESULTS

The complex, time-constrained, decision-making situations embodied in the experimental scenarios resulted in a large number of decision errors. The mean number of tactically significant errors documented across 6 teams and 4 scenarios was 14; the number of errors ranged from 9 to 22. The

standard deviation was 3.7. Subjects performed an average of 50 percent of the required behaviors as specified in the ROE. The ordinal agreement between three raters (navy subject matter experts) on error count ranks from TapRoot® analyses was computed. Results showed a high degree of agreement with the Kendall's W of 0.93, indicating that 93 percent of the possible rank variance is accounted for.

Decision-Making Errors

Detailed examinations of the information-processing sequences performed during tactical decision-making have revealed a variety of errors. On average, subjects failed to take required actions about half of the time. Explanations based in the cognitive psychology literature have been pursued, since a major goal of the TADMUS program is to develop a DSS based on an understanding of the way human decision makers actually process information under rapidly evolving situations.

The majority of documented errors involved errors of omission, that is, "failure to take defensive measures" and "failure to adhere to ROE." Failure to take defensive measures included failure to take actions to defend own-ship when an approaching aircraft had reached its weapon's release range. An example involved a case where two contacts were within the specified ROE limit, yet no action had been taken. The types of actions included in the "failure to adhere to ROE" category include failure to take action concerning the following listed and defined items:

- a. **Issuing warnings** is part of the usual identification process and involves three levels of warnings with increasing levels of urgency.
- b. **Establish friendly-force criteria** refers to establishing a plan with other friendly ships in the area to coordinate how they will respond to potential threats.
- c. **Changes in kinematics/identification friend or foe**—subjects are expected to notice significant kinematic changes and/or identification friend or foe parameter changes.
- d. **Other identification procedures** includes actions such as illuminating with fire-control radar.

The other major category of tactically significant error involved "loss of SA." These loss of SA errors were grouped under errors of commission and errors of omission and then further categorized into subgroups. Fifty-five percent of the loss of SA errors involved taking the wrong action (error of commission), while 45 percent of the errors involved failing to take some required action (error of omission). Error categories included under errors of commission involved incorrectly engaging a track (3 percent), incorrectly warning a track (29 percent), other incorrect actions (16 percent), and incorrect reporting (7 percent). The two instances of incorrectly engaging an aircraft, which were F-1 Mirage aircraft, were considered errors because the decision maker failed to take certain actions prior to engaging—not necessarily because the aircraft should not have been engaged. The actions that the decision makers failed to take involved ascertaining the identification of the aircraft for one case and failure to warn and illuminate the aircraft prior to engaging for the second case. Most instances of incorrectly issuing warnings to the aircraft involved issuing the warning when the aircraft was within its territorial airspace (that is, inside the 12-nautical-mile limit which is internationally recognized as under control of that nation) or issuing a warning at a level different from what was required. Other incorrect actions included illuminating the aircraft, "locking up" with radar, or ordering the aircraft to divert when the aircraft was still within its territorial airspace. Incorrect reporting involved inaccurate reports on the status of the tactical situation (such as indicating to the battle-group commander that

certain actions had been taken when they had not, misidentification of an aircraft, or omitting critical tracks from a report).

Errors of omission categorized under the “loss of SA” category included (a) failure to identify or attend to a contact; (b) failure to take action (e.g., to issue “hold-fire” when a contact turned outbound); (c) failure to recognize a threat (e.g., designating an aircraft as a nonthreat because it had passed its closest point-of-approach, yet it was still within missile-launch range); (d) instances of confusion or forgetting (e.g., forgetting or ignoring critical data, forgetting whether or not the aircraft had been warned, illuminated, or “locked-on,” or forgetting the aircraft’s response, or lack of response to these actions, forgetting the status of a contact, and confusing contacts); (e) misperception of data (e.g., reporting a contact as turning outbound when it is still inbound); (f) unclear communication (issuing vague orders regarding actions to be taken by a team member, such as failure to specify which weapon system is to be used or which contact is to be engaged).

Cognitive Explanations

The cause of failures to take required actions is, in many cases, attributed to the extremely high task demands levied on the decision maker by the scenario and the human decision maker’s limited attentional resources. Many cases are also attributed to working-memory limitations. Maintaining an awareness of the status of each contact and the status of many actions to be taken by the anti-air-warfare team—which actions have been taken and what the contact’s response to the action was—severely taxes the decision maker’s working memory. The high workload entailed in the scenarios produces a highly time-compressed decision-making situation. This time-compressed decision-making situation—where attentional resources and working-memory capacity are limited—do not allow the decision maker to maintain accurate SA for all tracks at any given time. We anticipate that the decision support modules in the DSS will mitigate these types of errors.

Human information-processing capabilities are not well suited to dealing with a “multiplicity of simultaneous and disjointed tasks. Thoughtful attention is modular: People can consciously think about only one thing at a time” (Adams et al., 1995, p. 92). As a result, they do not handle interruptions very well. Research indicates that when an operator is faced with as few as two tasks consisting of merely detecting or recognizing simple signals, a cost may be incurred in terms of a significant loss in sensitivity or time that can be allocated to either by the requirement to divide or switch attention between them (Broadbent, 1957; Schneider & Detweiler, 1988; Swets, 1984).

The memory demands of managing complex, multitask situations can easily surpass human limitations. The decision maker must not forget any of the contacts or tasks requiring action. In addition to remembering all the tasks needing attention, however, are the complexities entailed in keeping track of the data and substeps associated with each contact and prior action. The aviation literature provides many examples of incidents with explanations similar to the root causes for errors that were found in the TADMUS program. One category includes the potentially disastrous effects of interruptions in the task for air traffic controllers and pilots. Similarly, in the AAW environment, momentary intervening attention to another task or contact, or an interruption in a procedure, can leave the procedure or processing of a contact incomplete with potentially catastrophic results.

A fairly consistent pattern of tactical decision-making errors was documented from data collected during the baseline data-collection period. The root causes of these errors were traced to cognitive mechanisms such as limited attentional resources and working-memory limitations. By developing an

understanding of the pattern and types of errors most frequently observed in this task domain, we hope to provide a DSS that will mitigate these errors.

DECISION SUPPORT SYSTEM DESCRIPTION

A DSS was designed for naval shipboard command-level decision-makers to enhance decision making under the ambiguous, high-workload and high-tempo conditions characteristic of near-land operations. Design of the prototype DSS was based on (1) an understanding of the cognitive strategies people bring to bear when dealing with the types of decisions required in tactical decision-making and (2) applying human-system interface design principles which are expected to help compensate for human cognitive-processing limitations.

Major innovations are that the new DSS (a) helps the user anticipate future events by portraying the contact's history (not simply contact positions at separate time slices), (b) helps identify stored patterns of events, and (c) shows planned responses for anticipated events, thereby gaining time for the decision-maker (Tolcott, 1993). A corollary benefit is that the underlying design principles incorporated in the DSS provide a better match between those tasks performed by the computer and those performed by the human. For example, research indicates people are better at selecting and coding information than they are at integrating it (Dawes, 1971). The DSS is a data-fusion engine that presents all known information in a highly synthesized format.

Currently available decision support systems typically provide indications of the presence of various data items and their values. Indications of the relations between features, structural similarity between sequences of features, or evidence of underlying relationships among features is usually not depicted. The TADMUS decision-support tools were designed to provide precisely these types of evidence. All of the DSS modules focus on providing information to the user to support situation awareness. These modules will be discussed in terms of the underlying theoretical concepts and in terms of the expected payoff for each decision-support tool.

The experimental DSS receives tactical-data input from many sources, integrates the data to present a coherent picture, and displays it in various ways for aiding various subtasks. (These tactical data are inserted directly into the DSS from the scenario generator in the DEFTT Laboratory. This information would come from the sensor systems found aboard ship in the operational application of DSS.)

DECISION SUPPORT SYSTEM MODULES

The DSS was developed for the command-level decision makers—the commanding officer and the tactical action officer—within a Navy combat information center. These two officers are responsible for the following combat-related decisions: (1) recognizing and correctly interpreting the nature of the threat, (2) predicting which preplanned responses and/or countermeasures may be effective if the situation evolves in certain ways, and (3) interpreting information to determine whether the situation is actually evolving in a particular way. An additional task is to ensure that team members provide critical information that would enable the team to resolve ambiguities. The six modules making up the DSS were designed to facilitate the decision-maker's performance of the tasks listed above and, in general, to promote an accurate situation awareness while minimizing the decision maker's cognitive-processing requirements.

The layout for the prototype DSS display modules is shown in figure 1. These modules are arranged in an increasing level of information complexity from the top of the display to the bottom. The top half of the display contains the track summary, track history, and the response manager modules. (The track history module occupies the rectangle in the upper-right corner and in the circular

Track Summary	Track History	
Track History	Response Manager	
Basis for Assessment		Comparison to Normal Values
Track Priority List and Alerts		

Figure 1. Decision Support System Modules.

display below track summary in the upper left. These two areas present different views of the same information and are thus considered as one module.) These three modules focus on analyzing and identifying a single contact and would be used to make a quick shoot/no-shoot decision. The lower half of the display presents the basis for assessment, comparison to normal values, and the track priority list and alerts modules. Basis for assessment and the comparison to normal values modules provide more detailed analysis of a single contact, while the track priority list and alerts module (bottom of the display) presents information on all contacts currently requiring attention or action. The actual prototype DSS comprises the six display modules shown in figure 2.

Track Summary

Track summary presents the same contact parametric information current systems provide, but with an improved human-computer interface format and the addition of a DSS threat-assessment capability. Here, all data items are appropriately labeled and aligned to aid the user in extracting key parameters.

Track History

When a rapid decision is required to determine whether the contact should be engaged, the track history and response manager modules should present useful assistance in two ways: by facilitating the decision maker's use of a recognitional strategy when developing a threat assessment (via track history) and by assisting the decision maker in performing the requisite actions. For tasks involving rapid decision-making (such as several seconds to 1 or 2 minutes), a recognitional strategy appears to be highly efficient (Klein, 1993). The track history module was designed to support the recognition-primed decision model of decision-making. To generate a reasonable course of action, the decision maker must accurately identify familiar elements in the situation. The objective for this module is to facilitate the contact identification process by providing information integrated to support a recognitional decision strategy. The track history module presents a highly synthesized view of the situation concerning a specific contact.

The track history module depicts a contact's speed, altitude, course, and range on a two-dimensional graphical display, along with a geometric representation of both the contact's weapon-release envelope and own-ship's weapons coverage. A large amount of parametric data is portrayed graphically for rapid assimilation by the user. The track history module is designed to be used when the decision-maker has to make a rapid shoot/no-shoot decision. Changes in the contact's speed, course,

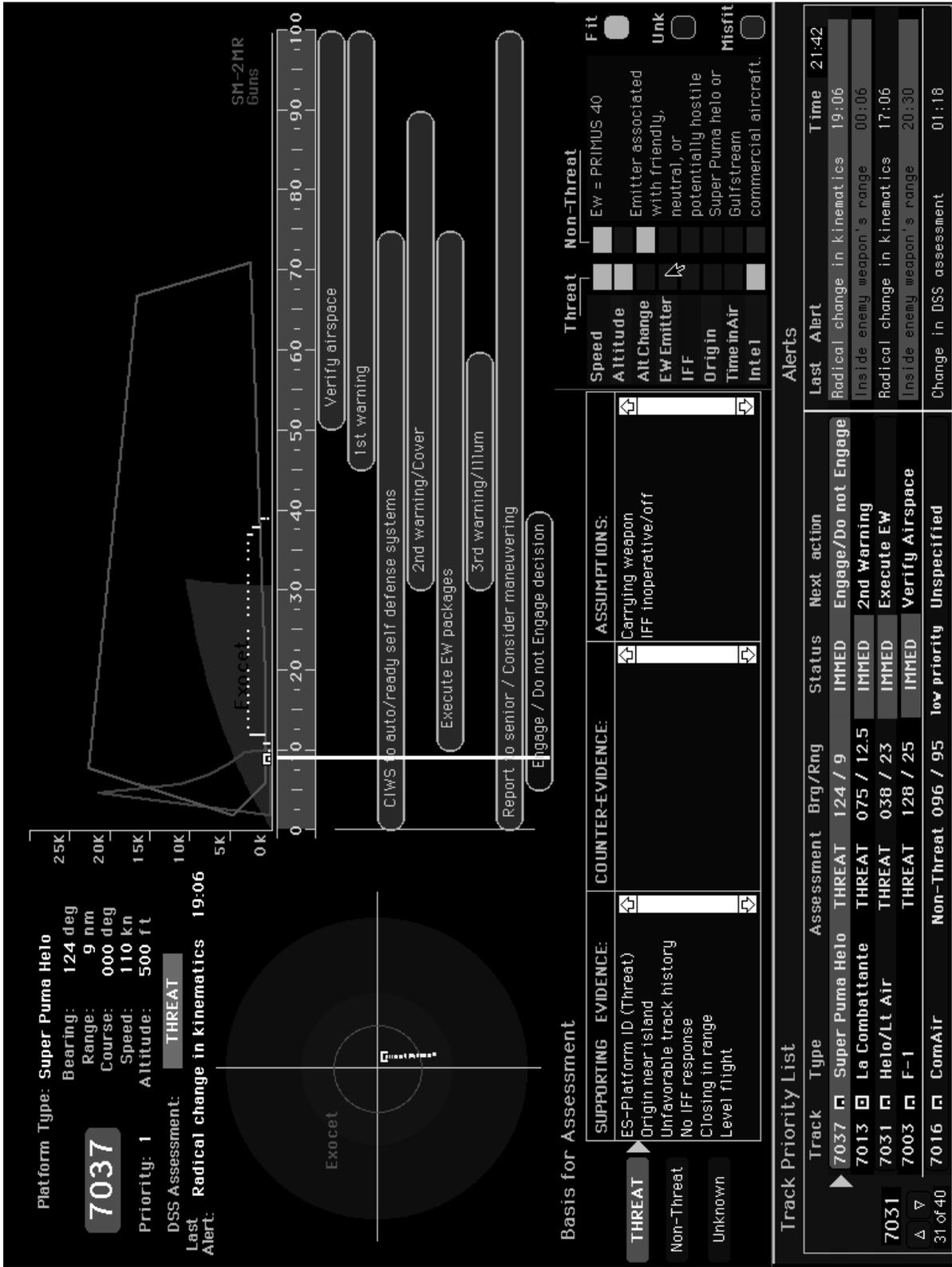


Figure 2. The Decision Support System Display.

altitude, or range are immediately apparent with this graphical depiction of the track history. This graphical representation was hypothesized to be particularly useful, because in previous systems the user had to remember the previous parameter values (e.g., altitude) and compare it with the current values for those parameters. However, as short-term memory degrades under stress, the user may not be able to accurately perform this function.

There are many well-documented instances of critical systems or parameter changes going unnoticed or unheeded, because the operating procedures, or the human-machine interface, provided no historical trace. For example, an unnoticed increase in altitude contributed to the shoot down of the Iranian airbus—when the team mistakenly believed the aircraft to be descending—because there was no historical trace to make the aircraft's actual *increasing* altitude apparent (Dotterway, 1992).

Response Manager

The response manager provides assistance in using preplanned responses. This decision support module was designed specifically to mitigate errors documented in previous research (Hutchins & Kowalski, 1993; Hutchins & Westra, 1995). The response manager was developed to (1) provide support to the user regarding required actions and when they need to be taken and (2) to lessen the task load imposed on the user's limited attentional resources during high-contact density. The following tasks severely tax the decision-maker's working memory: maintaining an awareness of the status of each contact and the status of many actions to be taken by the CIC team (e.g., issuing warnings, illuminating with radar, executing electronic-support measures packages, verifying airspace, readying self-defense systems, making reports to the battle-group commander, etc.)—as well as remembering the contact's response to these various actions.

During TADMUS baseline runs, the majority of documented errors involved errors of omission. These included the failure to take defensive measures, failure to adhere to ROE, as well as about half of the loss of SA errors. (See Hutchins & Westra, 1995, for a detailed coverage of the documented errors.) The cause of these failures to take required actions is, in many cases, attributed to the very high-task demands levied on the decision maker by the scenario. The scenarios were intentionally developed to be highly stressful (albeit realistic) by including high levels of ambiguity, workload, and time-pressure. The phenomenon that increasing stress leads to decreasing working memory is well documented (e.g., Hockey, 1986). Effective maintenance of the queue of pending tasks requires considerable cognitive effort.

Competent management of the task constellation requires that the decision maker respond to each task, ideally, at the most efficient possible moment or, minimally, before it is too late. This requires the person to stay abreast of the urgencies, opportunities, and constraints on all of the tasks. The response manager module graphically depicts preplanned responses that need to be taken for a selected contact, using a series of bars (on a range scale) that show the earliest and latest time each action can be taken to be effective. This module also depicts the contact's current speed and range via a moving pointer that indicates where the contact is in relation to the various actions which need to be taken. The response manager module thus cues the decision maker to take actions specified by the ROE or ship's battle orders. Color coding is used to keep track of which actions have been taken and which actions remain to be taken.

Basis for Assessment

Basis for assessment is based on a model of a cognitive strategy employed in making decisions where the decision maker is confronted with a situation involving contradictory or incomplete

information. In this situation, the decision maker constructs a causal model that explains the available evidence. This strategy is known as explanation-based reasoning, or story generation (Pennington & Hastie, 1993). In this approach, available data are assembled into explanatory structures, with one structure for each possible conclusion. Each of the explanations attempts to explain how every piece of data can be accounted for in support of each conclusion, even though some of the data items would naturally contradict reaching some conclusions. Contradictory data are explained through the use of internal assumptions. A fixed number of predefined possible conclusions are assumed, and each data item points directly to one of those possible conclusions.

Avoiding Decision Biases. Basis for threat assessment provides a contact threat assessment and presents all the information used to form the assessment. Threat assessment will usually generate multiple hypotheses to explain the available evidence. This occurs because many of the contacts behave in a way that greatly complicates determining whether they are a threat or nonthreat due to the inherent ambiguity in the scenarios. In addition to reflecting a naturalistic decision strategy based on explanation-based reasoning, this decision support module should have the corollary benefit of reducing decision bias. Human decision-makers have been shown to be deficient in generating alternatives. Specifically, in situation assessment they tend to generate only a few hypotheses based on early data and find it difficult to enlarge their hypothesis set, even in the face of contradictory data (Tolcott, 1991). Threat assessment presents all the supporting evidence, counter-evidence, and assumptions the decision maker would need to accept the presented hypothesis (that is, threat or nonthreat). The advantage is that the decision maker should be less susceptible to many of the typical biases which are well documented in the decision-making literature, such as “availability” bias, “confirmation” bias, effects of “framing,” etc. (Kahneman, Slovic, & Tversky, 1982).

By presenting all available evidence in a structured way, grouped under the three evidence categories mentioned above, the decision maker is less likely to make a decision based on a subset of the available evidence. The decision-maker will also be made explicitly aware of the absence of data that may be as important as the presence of data. For example, when studying Army intelligence analysts, it was found that the confirmation bias could be reduced by displays that made explicit the uncertainties about enemy-unit locations (Tolcott & Marvin, 1988). In research conducted to investigate whether Navy decision-makers responding to antiair-warfare scenarios would be susceptible to these biases, the results supported earlier research findings. A study was designed to assess whether naval personnel, trained and experienced in antiair operations, exhibit biases when performing their normal duties. Results strongly supported existence of the availability, representativeness, contrast, and confirmation biases in the surface antiair warfare context (Barnett, Perrin, & Walrath, 1993). Basis for assessment should help ameliorate the effects of these pervasive biases.

Avoiding “Blue-On Blue” Engagements. A second advantage of the basis for assessment module is that it should reduce the occurrence of “blue-on-blue” incidents (fratricide) where a decision maker mistakenly identifies a friendly contact as an enemy. The decision maker may be better able to weigh all the information about a contact and reach a more accurate assessment regarding its threat potential when the DSS does the following: points out the counter-evidence associated with a particular threat assessment category and lists the assumptions one has to “buy into” to accept the conclusion that the contact is a threat.

Comparison to Normal Values

The comparison to normal values module compares known information about a contact with information representative of specific types of contacts. This module was designed to support the user

in performing feature matching. Klein and associates (Klein, 1993) found feature matching to be the predominant cognitive strategy used by decision makers when performing situation assessment. The decision maker matches the features of the present situation with a template, or mental model, of a previous situation. Comparison to normal values presents a comparison of data associated with the selected contact with exemplars for other types of contacts (i.e., threat or nonthreat) and graphically depicts whether the selected contact is a fit or misfit with these categories. Discrete coding of key variables is used to determine whether a contact's data fall within the specific ranges that categorize threat versus nonthreat.

Track Priority List and Alerts

The track priority list and alerts module focuses on several contacts at once and allows the user to monitor more than one contact. This module presents multiple-contact information, focusing on high-priority contacts, the next action to be taken and status of that action (e.g., immediate, watch, low priority), the last alert given concerning the contact and the time it was given, and an alert-history function. The user can click on the last alert to view a history window that displays all previous alerts received regarding this contact. Alerts are based on preset criteria for key events and required responses. Lines included in this decision support module are ordered by the operational priority assigned to the corresponding contact.

One type of tactically significant error observed during early TADMUS experiments was a failure to attend to a contact of interest. This is attributed to the high workload imposed by the ambiguous contacts and the very limited time decision makers have to process contacts. The track priority list and alerts module was designed to ensure that the user is made aware of new contacts of interest and their status. This module will prompt the user on required actions and specify when these actions are to be taken. The behavior that triggered the last alert is also presented along with the capability to review the history of alerts for any selected contact.

DECISION SUPPORT SYSTEM FEATURES

In summary, key features of the prototype DSS include the ability to:

- Track multiple hypotheses
- Present patterns of tactical activities
- Develop explanations for observed events
- Evaluate the plausibility of explanations
- Use graphics to support intuitive processes and reduce cognitive-processing requirements
- Prompt the user for appropriate responses
- Support the decision maker's cognitive process

DISCUSSION

Failure to take appropriate actions may be explained by the limited resource capacity of human memory. In these scenarios, a large number of contacts are monitored for changes in any of several key parameters. Three modules in the DSS are hypothesized to assist with recognizing a problem and taking the appropriate actions: the track history, the response manager, and the track priority list and alert modules.

Features offered by the DSS to address errors attributed to limited attentional resources include focusing attention on (1) high-priority contacts (i.e., track priority list and alerts), as well as on (2) missing data (e.g., basis for assessment), and (3) enabling the decision maker to use more data than are typically used in current systems (e.g., track history, comparison to normal values). Current systems require the user to retain previous contact data in memory to compare with current values for critical parameters. Current systems also require the user to rely on recalling vast amounts of information from training and experience. Presenting all known data on a contact in a synthesized way should reduce working-memory requirements and facilitate recognition. Additional potential performance-enhancement features, offered by the DSS, include displaying the complete kinematic contact history, presenting graphic displays of location and trends, highlighting missing data, providing alerts, and providing assessments of current contact identity that go beyond what existing systems currently present.

Focusing the user's attention on trend and history data should decrease the cognitive workload imposed by these scenarios where many contacts must be identified and responded to under severe time constraints. Similarly, delineating trend and history data can assist in identifying a contact where noticing changes in critical parameters is essential. Presentation of trend and history data, as well as basis for assessment and comparison to normal values, should also mitigate cognitive "tunnel-vision" effects, where the decision maker attends to a smaller number of cues when under stress.

The notion of time is an important characteristic of situation awareness (Harwood, Barnett, & Wickens, 1988). The past is critical to understanding the present, and both past and present information must be used to predict future events (Shrestha et al., 1995). Endsley (1988) referred to the "projection of their (perceived elements) status in the near future" when discussing situational awareness. However, Endsley also noted the task of attending to incoming information and subsequently predicting future events places a heavy load on working memory. Several decision support modules were developed to assist the user in remaining aware of the contact's history and changes over time. Remembering which actions are to be taken at what time levies an additional burden by placing a heavy load on working memory. A secondary time savings should be achieved by the DSS acting as an intelligent "advisor," that is, by assisting the decision maker in knowing what actions to take, when to take them, and which actions have already been taken. A tertiary time savings can be achieved by including a template depicting the weapons' release ranges so the decision maker does not need to rely on fallible human memory or querying a team member about weapons ranges. Information-processing time can be saved for the decision maker by having the DSS graphically depict a synthesized view of the contact's behavior over time, along with the contact's weapons envelope in relation to both own-ship's radar and weapon coverage.

CONCLUSIONS

The research reported here focuses on developing a DSS that reflects the natural decision-making strategies of humans. Presenting synthesized information in the form of graphic presentations is expected to reduce the cognitive-processing load for the decision maker when performing situation assessment. The intention is to aid the decision maker by providing information in a way that will minimize the need to maintain information in working memory, reduce information-processing demands, help focus attentional resources on the highest priority contacts, remind the user to take needed actions, help make decisions under stress, and support higher levels of situation awareness.

Decision support systems require that the human's strengths be used in synergy with the advantages offered by the DSS. Limitations associated with the current generation of automated decision aids include the idea that (1) they cannot adequately capture the expertise developed by experience over time and (2) since all contingencies cannot be anticipated, the expert's abilities to use intuition is indispensable (Mosier, 1996). Mosier's review of the limitations of automated decision systems delineates the characteristics of human expertise that surpass the capabilities of automated systems. These include the human capacity for creativity, adaptability, the ability to incorporate experience, the presence of a broad focus, analogical reasoning, and common-sense knowledge. The goal for the DSS is to capitalize on the strengths of the human along with the advantages provided by the decision support system.

TESTING THE DSS

The prototype DSS display modules are currently being empirically evaluated in the simulated tactical environment provided in the DEFTT Laboratory. Experienced naval decision makers engage in experimental scenarios with and without access to the DSS display. The various decision support modules will be tested individually and in combination in future experiments. The following information will be collected: data on reduction of errors, improvements in users' situation awareness scores, changes in communication patterns, and subjective responses to the decision support system.

FUTURE RESEARCH

While tools based on both the recognition-primed decision and explanation-based reasoning models of decision-making are included in the DSS, no direct connection exists between the two. Research is currently being conducted to extend schema theory to dynamic decision-making situations. This involves developing and testing a hybrid model of cognitive behavior in decision-making to incorporate both types of knowledge, i.e., feature matching and story generation, as elements of the same schema model of naturalistic decision-making (Smith & Marshall, in press). Schema theory, as described by these authors, offers a context for integrating these two models that have typically been viewed as separate entities.

REFERENCES

- Adams, M. J., Tenney, Y. J., and Pew, R. W. 1995. "Situation Awareness and the Cognitive Management of Complex Systems," *Human Factors*, 37(1), pp. 85-104.
- American Psychological Association (APA). 1988. *Science Agenda*, Fall.
- Barnett, B. J., Perrin, B. M., and Walrath, L. D. 1993. "Bias in Human Decision-Making for Tactical Decision-Making Under Stress." (Task 1). St. Louis, MO. McDonnell Douglas Corporation.
- Bower, G. H. 1970. "Organizational Factors in Memory," *Cognitive Psychology*, 1, pp. 18-46.
- Broadbent, D. E. 1957. "A Mechanical Model for Human Attention and Immediate Memory," *Psychological Review*, 64, pp. 205-215.
- Buck, L. 1989. "Human Error at Sea," *Human Factors Bulletin*, September, 32 (9), p. 12.
- Casey, S. 1993. *Set Phasers on Stun and Other True Tales of Design, Technology, and Human Error*. Aegean Publishing Company, Santa Barbara, CA.
- Casner, S. 1991. "Task-Analytic Design of Graphic Presentations." Technical Report AIP-145. Departments of Computer Science and Psychology, Carnegie Mellon University and Learning Research and Development Center, University of Pittsburgh, PA.
- Cohen, M. S. 1993. "The Bottom Line: Naturalistic Decision Aiding." In G. Klein, J. Orasanu, R. Calderwood, and C. E. Zsombok (Eds.) *Decision-Making in Action: Models and Methods* (pp. 138-147). Ablex Publishing Corporation, New Jersey.
- Dawes, R. M. 1971. "A Case Study of Graduate Admissions: Application of Three Principles of Human Decision-Making," *American Psychologist*, 34, pp. 571-582.
- Dotterway, K. A. 1992. "Systematic Analysis of Complex Dynamic Systems: The case of the USS *Vincennes*." Unpublished master's thesis, Naval Postgraduate School, Monterey, CA.
- Endsley, M. R. 1988. "Design and Evaluation for Situational Awareness Enhancement," *Proceedings of the Human Factors 32nd Annual Meeting*, pp. 97-101.
- Federico, P. A. 1995. "Expert and Novice Recognition of Similar Situations," *Human Factors*, 37 (1), pp. 105-122.
- Fogerty Report: Formal Investigation into the Circumstances Surrounding the Downing of a Commercial Airliner by the USS *Vincennes*, by Rear Admiral William M. Fogerty, USN, 28 July 1988, pp. 4, 6. Hereafter referred to as the Fogerty Report.
- Gruner, W. P. 1990. "No Time For Decision Making," *U.S. Naval Institute Proceedings*, pp. 39-41.
- Harwood, K., Barnett, B., and Wickens, C. 1988. "Situational awareness: A Conceptual and Methodological framework," *Proceedings of the Symposium on Psychology in the Department of Defense*.

- Hockey, G. R. 1986. "Changes in Operator Efficiency as a Function of Environmental Stress, Fatigue, and Circadian Rhythms." In: K. R. Boff, L. Kaufman, J. P. and Thomas (Eds.): "Handbook of Perception and Human Performance." Wiley, New York.
- Hutchins, S. G. (1996). "Decision Making Evaluation Facility for Tactical Teams." NRaD TR. Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA. (In press).
- Hutchins, S. G. and Kowalski, J. T. 1993. "Tactical Decision Making Under Stress: Preliminary Results and Lessons Learned," *Proceedings of the 10th Annual Conference on Command and Control Decision Aids*, pp. 85-96. June 1993. Washington, D. C.
- Hutchins, S. G. and Rummel, B. K. 1995. "A Decision Support System for Tactical Decision Making Under Stress," *Proceedings of the First International Conference on Command and Control Research and Technology*, pp. 163-173. June 1995. Washington, D. C.
- Hutchins, S. G. and Westra, D. P. 1995. "Patterns of Errors Shown by Experienced Navy Combat Information Center Teams," *Proceedings of the 39th Annual Meeting of the Human Factors and Ergonomics Society*, pp. 454-458. October 1995. San Diego, CA.
- Hutchins, S. G. and Westra, D. P. 1995. "TADMUS Baseline Experimental Results." NRaD TR. Naval Command, Control and Ocean Surveillance Center, RDT&E Division. (In preparation) San Diego, CA.
- Kaempf, G. L. and Militelo, L. G. 1992. "Decision Making in Emergencies," First Offshore Installation Management Conference: Emergency Command Responsibilities Collected Papers, Aberdeen, Scotland.
- Kaempf, G. L. , Wolf, S., and Miller, T. E. 1993. "Decision Making in the Aegis Combat Information Center," *Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting*, pp. 1107-1111. Santa Monica, CA: Human Factors and Ergonomics Society.
- Kahneman, D., Slovic, P., and Tversky, A. (Eds.) 1982. "Judgment Under Uncertainty: Heuristics and Biases." Cambridge: Cambridge University Press.
- Kirshenbaum, S. S. 1992. "Influence of Experience on Information-Gathering Strategies," *Journal of Applied Psychology*, 77, pp. 343-352.
- Klein, G. A. 1989. "Recognition-Primed Decisions." In W. R. Rouse (Ed.) *Advances in Man-Machine System Research*, pp. 47-92, vol. 5, pp. 47-92. JAI Press, Inc., Greenwich, CT.
- Klein, G. A. 1993. "A Recognition-Primed Decision (RPD) Model of Rapid Decision Making." In G. A. Klein, J. Orasanu, R. Calderwood, and C. E. Zsombok (Eds.) *Decision Making in Action: Models and Methods*, pp. 138-147. Ablex Publishing Corporation, NJ.
- Larkin, J. H. and Simon, H. A. 1987. "Why a Diagram is (Sometimes) Worth 10,000 Words," *Cognitive Science*, 11, pp. 65-99.
- Mosier, K. L. 1996. "Myths Associated with Automated Decision Aids." In C. E. Zsombok and G. A. Klein (Eds.) *Advances in Naturalistic Decision Making: Research and Applications*. Hillsdale, NJ: Erlbaum.

- Mundy, C. E., Jr. 1994. "Thunder and Lightning: Joint Littoral Warfare," *Joint Force Quarterly*, 4, pp. 45-50, Spring.
- Noble, D. 1989. "Application of Theory of Cognition to Situation Assessment." Vienna, VA: Engineering Research Associates.
- Noble, D. 1993. "A Model to Support Development of Situation Assessment Aids." In G. A. Klein, J. Orasanu, R. Calderwood, and C. E. Zsombok (Eds.) *Decision Making in Action: Models and Methods*, pp. 287-305. Ablex Publishing Corporation, New Jersey.
- Norman, D. A. 1988. "The Psychology of Everyday Things." Basic Books, Inc. New York.
- Norman, D. A. and Bobrow, D. G. 1975. "On the Data-Limited and Resources-Limited Processes," *Cognitive Psychology*, 7, pp. 44-64.
- Office of Naval Technology. 1992. "FY 1993 Program Plan for Tactical Decision Making Under Stress." July 1992. Arlington, VA.
- Orasano, J. and Connolly, T. 1993. "The Reinvention of Decision Making." In G. A. Klein, J. Orasanu, R. Calderwood, and C. E. Zsombok (Eds.), *Decision Making in Action: Models and Methods*. Ablex Publishing Corporation. Norwood, NJ.
- Paradies, M. 1991. "Root Cause Analysis and Human Factors," *Human Factors Society Bulletin*, 34 (8), pp. 1-4.
- Paradies, M. and Unger, L. 1991. "TapRoot Incident Investigation System Manual." Vol. 1-7. System Improvements, Inc., Knoxville, TN.
- Pennington, N. and Hastie, R. 1992. "Explaining the Evidence: Tests of the Story Model of Decision Making," *Journal of Personality and Social Psychology*, vol. 62, no. 2, pp. 189-206.
- Pennington, N. and Hastie, R. 1993. "A Theory of Explanation-Based Decision-Making." In G. A. Klein, J. Orasanu, R. Calderwood, and C. E. Zsombok (Eds.) *Decision Making in Action: Models and Methods*, pp. 188-201. Ablex Publishing Corporation, Norwood, NJ.
- Perrow, C. 1984. "Normal Accidents: Living with High Risk Technologies." New York, Basic Books, Inc.
- Rasmussen, J. 1986. "Information Processing and Human-Machine Interaction." In A. P. Sage (Ed.) Series vol. 12, North-Holland, Amsterdam.
- Roberts, N. C. and Dotterway, K. A. 1995. "The Vincennes Incident: Another Player on the Stage?" *Defense Analysis*, vol. 11, no. 1, pp. 31-45.
- Salthouse, T. A. 1992. "Cognition and Context," *Science*, 257, pp. 982-983.
- Sarter, N. B. and Woods, D. D. 1991. "Situation Awareness: A Critical But Ill-Defined Phenomenon." *The International Journal of Aviation Psychology*, 1 (1), pp. 45-57.
- Schneider, W. and Detweiler, M. 1988. "The Role of Practice in Dual-Task Performance: Toward Workload Modeling in a Connectionist/Control Architecture," *Human Factors*, 30, pp. 539-566.

- Senders, J. W. and Moray, N. P. 1991. "Human Error: Cause, Prediction, and Reduction." Lawrence Erlbaum Associates, NJ.
- Shrestha, L. B., Prince, C., Baker, D. P., and Salas, E. 1995. "Understanding Situation Awareness: Concepts, Methods, and Training." *Human/Technology Interaction in Complex Systems*, vol. 7, W. B. Rouse (Ed.). JAI Press. San Francisco.
- Simon, H. A. 1978. "Information-Processing Theory of Human Problem Solving." In W. K. Estes (Ed.), *Handbook of Learning and Cognitive Processes*, vol. 5, Human Information Processing, Wiley. New York.
- Smith, D. E. and Grossman, J. D. 1993. "Understanding and Aiding Decision Making in Time-Constrained and Ambiguous Situations." Unpublished manuscript.
- Smith, D. E. and Marshall, S. (In press.) "Applying Hybrid Models of Cognition in Decision Aids." In G. A. Klein and C. E. Zsombok (Eds.) *Advances in Naturalistic Decision Making: Research and Applications*. Hillsdale, NJ: Erlbaum.
- Swets, J. A. 1984. "Mathematical Models of Attention." In R. Parasuraman and R. Davies (Eds.), *Varieties of Attention*, pp. 183-242. Academic, NY.
- Tolcott, M. A. and Marvin, F. F. 1988. "Reducing the Confirmation Bias in an Evolving Situation." Interim Technical Report 88-11. Decision Science Consortium, Inc., Reston, VA.
- Tolcott, M. A. 1991. "Understanding and Aiding Military Decisions." Office of Naval Research, European Office, *27th International Applied Psychology Symposium*, Stockholm, Sweden.
- Wilson, G. L. and Zarakas, P. 1978. "Anatomy of a Blackout," *IEEE Spectrum*, February 1978, pp. 339-346.

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